

UNCLASSIFIED

AD NUMBER
ADB256808
NEW LIMITATION CHANGE
TO Approved for public release, distribution unlimited
FROM Distribution authorized to U.S. Gov't. agencies only; Administrative/Operational Use; AUG 2000. Other requests shall be referred to Commander, U.S. Army Soldier and Biological Chemical Command, [SBCCOM], Natick Soldier Center, Kansas St., Attn: AMSSB-RIP-F, Natick, MA 01760-5018.
AUTHORITY
ASBCC, per DTIC Form 55, 4 Aug 2005

THIS PAGE IS UNCLASSIFIED



TECHNICAL REPORT
NATICK/TR-00/015L

AD _____

BATTLEFIELD FLAME/THERMAL THREATS OR HAZARDS AND THERMAL PERFORMANCE CRITERIA

by
Il Young Kim

August 2000

Final Report
October 1998 - September 1999

Distribution authorized to U.S. Government agencies only; Administrative or Operational Use, August 2000. Other requests for this document shall be referred to Commander, U.S. Army Soldier and Biological Chemical Command, (SBCCOM), Natick Soldier Center, Kansas St., ATTN: AMSSB-RIP-F, Natick, MA 01760-5018

**U.S. Army Soldier and Biological Chemical Command
Soldier Systems Center
Natick, Massachusetts 01760-5018**

DTIC QUALITY INSPECTED 4

20000814 074

DISCLAIMERS

The findings contained in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

DESTRUCTION NOTICE

For Classified Documents:

Follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For Unclassified/Limited Distribution Documents:

Destroy by any method that prevents disclosure of contents or reconstruction of the document.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) August 2000		2. REPORT TYPE FINAL		3. DATES COVERED (From - To) October 1998 - September 1999	
4. TITLE AND SUBTITLE BATTLEFIELD FLAME/THERMAL THREATS OR HAZARDS AND THERMAL PERFORMANCE CRITERIA				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
				5d. PROJECT NUMBER AH98	
6. AUTHOR(S) IL YOUNG KIM				5e. TASK NUMBER 907MFB	
				5f. WORK UNIT NUMBER N31340	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Soldier and Biological Chemical Command (SBCCOM) Natick Soldier Center Kansas Street ATTN: AMSSB-RIP-F Natick, MA 01760-5018				8. PERFORMING ORGANIZATION REPORT NUMBER NATICK/TR-00/15L	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution authorized to U.S. Government only; Administrative and Operative Use, August 2000. Other requests for this document shall be referred to: Commander, U.S. Army Soldier and Biological Chemical Command (SBCCOM) Natick Soldier Center, Kansas Street. ATTN: AMSSB-RIP-F(IL Young Kim). Natick, MA 01760-5018					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT There is a need for an improved bench-scale flammability test method that can not only measure the protection performance of military protective clothing more reasonably, but also can correlate other current test methods in getting more reliable and consistent results. Heat intensity, one of the major test parameters for the new test method, is to represent flame/thermal burn injury hazards encountered on the battlefield. A comprehensive understanding of military flame/thermal situations based on battlefield scenarios is essential to do this. This study will identify all flame/thermal threats or hazards expected on various battlefield environments. They will be characterized based on different combat situations, and their fuels and fire characteristics. Based on the results from this study, thermal performance criteria for new military protective clothing system will be recommended for the user groups. The criteria will be the basis of the test conditions for new improved test methods.					
15. SUBJECT TERMS <div style="display: flex; justify-content: space-between;"> <div>FLAMMABILITY TESTING PROTECTIVE CLOTHING MILITARY APPLICATIONS</div> <div>BATTLEFIELDS IDENTIFICATION THERMAL BURNS</div> <div>PROBABILITY EXPOSURE FLAMES</div> <div>VERTICAL FLAMMABILITY TEST BURN INJURIES THERMAL PERFORMANCE</div> </div>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 50	19a. NAME OF RESPONSIBLE PERSON IL YOUNG KIM
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (Include area code) (508) 233 - 4278

Table of Contents

	Page
List of Figures	v
List of Tables	vi
Preface	vii
Chapter 1. Introduction	1
Chapter 2. Flame/Thermal Protection on the Battlefields	3
a. Flame/Thermal Protective Clothing.....	3
b. Individual Soldier on the Battlefield.....	4
Mounted and Dismounted.....	4
Combat and Non-combat.....	5
Chapter 3. Flame/Thermal Threats	5
a. Flame/Incendiary Weapons	5
Flamethrowers	6
Incendiary Weapon	8
Fuel Air Explosive (FAE, Thermobaric)	9
Chapter 4. Flame/Thermal Battlefield Operations	9
a. Dismounted	9
b. Mounted	10
c. Military Operations in Urban Terrain (MOUT)	10
Chapter 5. Flame/Thermal Hazards	11
a. Burn Injury Hazards.....	11
Threat Generated Burn Hazards	11
Incidental Burn Hazards	12
Chapter 6. Fire Characteristics	13
a. Pool Fire	13
b. Spray Fire.....	16
c. Structural Fire.....	16
Chapter 7. Heat Flux for a Test	17
a. Time	18
b. Distance	19
c. Trade-off Analysis	21

Contents (Continued)

Chapter 8. Thermal Performance Criteria for Military Protective Clothing	
System	22
a. Heat Flux.....	22
b. Exposure Time.....	23
c. Percentage of Burn Injury.....	25
d. Recommendation	25
Chapter 9 Conclusions	27
Appendixes	
A. Flame Weapons for Different Conflict Intensity and Technology Ability	29
B. Weight and Cost of Current Military Protective Clothing System	33
C. Ammunitions Carried Inside Combat Vehicles and Tanks	35
D. Thermophysical Properties of Fuels Used on the Battlefield	37
Bibliography	39

List of Figures

Figure	Page
Figure 1. The Decision Tree	3
Figure 2. An Approach to Flame/Thermal Protection for Individual Soldier	4
Figure 3. Average Surface Emissive Power for Gasoline, Kerosene, and JP-4 Pool Fires (SFPE Handbook of Fire Protection Engineering)	13
Figure 4. Target Fluxes vs Fire Diameter	14
Figure 5. Steady State Target Heat Flux vs Vertical Vent Area	15
Figure 6. Heat Flux with Target Face at 45° Angle with Compartment Floor ...	15
Figure 7. Heat Flux Range for Various Flame/Thermal Incidents	17
Figure 8. Heat Flux vs Time	19
Figure 9. Heat Dose vs Distance (per kg of Propellant)	20
Figure 10. Trade-off Analysis	21

List of Tables

Table	Page
Table 1. Flame/Incendiary Weapons	6
Table 2. Flamethrowers	7
Table 3. Incendiary Agents and Types	9
Table 4. Flame/Thermal Burn Hazards Identified on the Battlefield	12
Table 5. Fire Characteristics for Battlefield Flame/Thermal Burn Injury Hazards	16
Table 6. Heat Flux for Various Fires	18
Table 7. Heat Fluxes and Exposure Time for Current Flammability Tests	23
Table 8. Escape Time for Current Military Operations	24
Table 9. Comparison of Current Flammability Test Methods	25

PREFACE

This study was conducted by Il young Kim, Multifunctional Material Team, U.S. Army Natick Soldier Center during the period of October 1998 through September 1999. The study was funded under program Test Methodology for Flame/thermal Properties of Materials (STO) (AMS CODE 622786, AH98).

The author wishes to thank the following individuals for their assistance during the study:

David Tucker, Supporting Science and Technology, U.S. Army SBCCOM

Sandra Hickey, Foreign Intelligence Office, U.S. Army SBCCOM,

Greg Skaff, U.S. Army Armor Center (Ft. Knox, TN)

Joseph Licina, U.S. Army, Aviation Center (Ft. Rucker, AL)

Al Harvey, U.S. Army, Infantry School (Ft. Benning, GA)

Robert Yobbs, National Ground Intelligence Center (NGIC)

John Redgate, Editor, U.S. Army SSCOM

BATTLEFIELD FLAME/THERMAL THREATS/HAZARDS AND THERMAL PERFORMANCE CRITERIA

Chapter 1 Introduction

Most current flammability test methodologies, originally developed for primary screening or rating of commercial flame-retardant fabrics, are not adequate to evaluate the performance of military protective clothing against flames/thermal burn hazards on the battlefield. Because of their different heat sources and test methodologies, each test has its own advantages and disadvantages and sometimes one test is better than others in some ways. But no single test is good enough for our military application.

The vertical flame test measures how fast a fabric sample ignites and burns. This method, an inexpensive and convenient way to initially rate fabric samples, has no access to burn injury measurement. Another popular bench-scale method is the thermal protection performance (TPP). This bench-scale test has a concept for the measurement of protective performance using Stall and Henriques' ¹ burn injury criteria. Its test condition, however, is not realistic. Its convective heat source simulating a real fire deforms fabric samples easily even before collecting critical data to understand heat transfer through the fabrics. A copper calorimeter detecting temperature changes on simulated skin surface has some limitations to detect burn injury after the exposure time. Of course, the expensive and complicated full-scale test has more functions than a bench-scale test does. PyroMan, a full-scale flammability test located at the North Carolina State University, is able to measure burn injury using skin sensors in real fire situations. But the calibration of 120 skin sensors is based on the assumption of the even distribution of convective heat sources around irregular surface of a mannequin that is almost impossible to achieve. The information of the location and the amount of burn injury from this test could be misleading. Each test has advantages and disadvantages in terms of convenience, cost, and capability, but no single method is good for most of them. In practice, there have been some inconsistencies and disagreements in test results. It is very confusing to evaluate a flame retardant fabric that passed the full-scale test while failing the vertical test.

There is a need for an improved flame/thermal test method that can measure the protection performance of clothing more reasonably and correlate other current test methods in getting more reliable and consistent results. The new test should have the convenience and economy of bench-scale test while keeping the potential of full-scale test. Also, the heat intensity for the new test method will simulate real battlefield flame/thermal burn injury hazards as much as possible. A comprehensive understanding of military flame/thermal situations on the battlefield is essential to do this.

The objective of this study is to identify and characterize all flame/thermal threats or hazards expected on various battlefield environments. They will be investigated based on different combat situations such as dismounted, mounted, and especially military operations in urban terrain (MOUT). This study will focus on burn injury flame/thermal hazards and military protective clothing systems. The categorization of battlefield

flame/thermal hazards into several groups of different fire characteristics is another way of identifying the most probable battlefield fire models.

The selection of heat flux for a military flammability test is a challenging task for justifying a single heat source to cover various flame/thermal burn injury hazards with a wide range of heat flux. This study will show why and how a single heat flux was selected for a test.

Based on the results from this study, thermal performance criteria for new military protective clothing systems will be recommended. The criteria expressed in terms of heat flux, exposure time and the percentage of burn injury will be the basis of the test conditions for new improved test methods.

Approach:



Chapter 2

Flame/Thermal Protection on the Battlefield

a. Flame/Thermal Protective Clothing

As demonstrated first by Tribus (1970), the burn injury hazard potential of a protective clothing fabric can be assessed in terms of probability. This probability is composed of the partial probabilities associated with the occurrence of possible events and circumstances leading from clothing to burn injury. Primary stochastic events dictated by human decisions or responses can be affected at best by appropriate doctrine, while the principally deterministic events of fabric ignition and fabric combustion depend strongly on fabric characteristics and therefore are amenable to direct improvement either by fabric screening or by alteration of fabric properties.²³

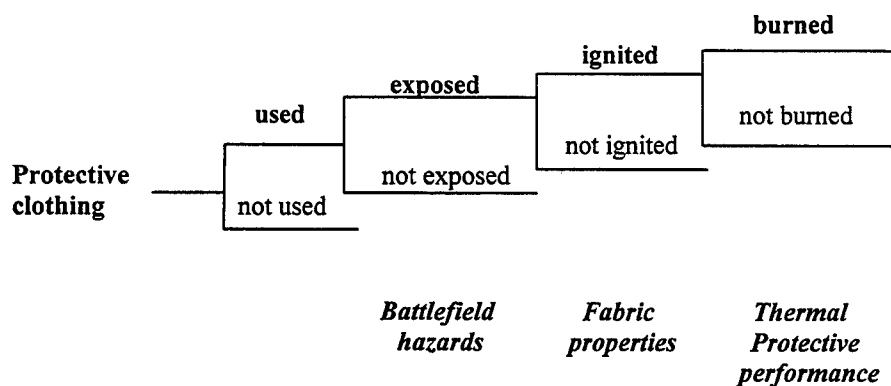


Figure 1. The Decision Tree

In a military situation, the probability of protective clothing being used could be decided by a policy regulating when the item should be used during battlefield operations. Currently, five different configurations of protective clothing are issued with mounted warriors, such as tankers, and aviators for the Army helicopter. Each configuration provides a different level of protection. Currently, no protective clothing is required for dismounted warriors. The chances to be exposed to the flame/thermal threats or hazards depend on combat missions: combat or non-combat (peacekeeping); mounted or dismounted; offensive or defensive positions.

When an Army protective garment is exposed to an ignition source (flame/thermal hazard), it may or may not ignite, and if it does ignite, it may cause burn injury to the wearer. The probability of clothing being ignited depends on the flammability (ignition and flame propagation) of clothing fabrics while burn injury probability depends on the thermal protection performance of the clothing fabrics where skin is covered. The

probabilities of ignition and burn injury could be reduced by selecting better flame retardant materials and effective heat transfer design to improve thermal performance of the protective clothing system.

An ideal clothing flammability test will be the one that can measure the probability of burn injury based on the thermal performance of protective fabric materials exposed to simulated battlefield flame/thermal hazards.

There are two major conditions deciding the probability of exposure to battlefield flame/thermal hazards: whether a soldier is in combat or not and if he is in a combat situation, what kind of environment he is operating in.

b. Individual Soldier on the Battlefield

Mounted and Dismounted are two groups of soldiers classified based on where they are operating at during combat situation. Mounted soldiers are soldiers who operate in the limited space of a combat vehicle or a helicopter cockpit. Tankers, combat vehicle crewmen (CVC), and aviators of Army helicopters belong to this group. Dismounted soldiers are infantrymen and engineers working in open field. Dismounted soldiers are open to all climatic conditions: wind, rain, snow, temperature and humidity. They can be attacked by the enemy with less warning but usually can escape from burn hazards with better chances than mounted soldiers. MOUT presents a combination of mounted and dismounted conditions in urban street and buildings environments. These three groups are one of the bases for the identification of flame/thermal hazards in the battlefield and the establishment of thermal performance criteria for protective clothing system.

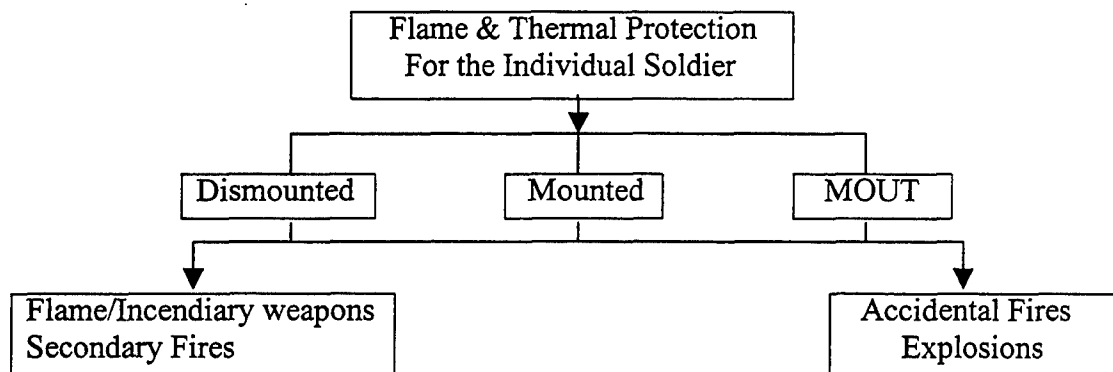


Figure 2. An Approach to Flame/thermal Protection for Individual Soldier

As you see from Figure 2, this concept is also an initial approach to the identification of flame/thermal threats in our DTO project titled, "*Flame/thermal protection for the individual soldier, Multifunctional fabric system*".

Combat and Non-combat

Whether an individual warrior is involved in combat or not is another parameter for the recognition of flame/thermal threats or hazards in the battlefield. Sometimes combat/non-combat is expressed as offensive/defensive activity. The most catastrophic but less probable flame/thermal threats to combat warriors are enemy flame/incendiary weapon systems. Non-combat flame/thermal situations are similar to civilian fire environments. Accidental fires from such combustible materials in the battlefield as fuel, oil, and lubricants are the major threats to non-combat warriors working in field kitchens, fuel deposits and barracks. Later, battlefield flame/thermal burn hazards will be identified based on this concept.

Chapter 3

Flame/Thermal Threats

According to the North Atlantic Treaty Organization (NATO) definitions, threat means the adversary potential to injure, in this case burn. Major flame/thermal threats on the battlefield can be enemy flame weapons and their delivery mechanism, doctrine, and use.²⁴

a. Flame/Incendiary Weapons

The United Nations Protocol III defines a flame weapon as any weapon system that uses hydrocarbons as its main source of fuel. These weapons require an igniter to ignite the fuel. A flamethrower that uses petroleum is a flame weapon. Petroleum-based flame agents possess high combustion heat, produce a large flame, and often generate large amounts of carbon monoxide. Easily ignited hydrocarbons, such as gasoline, are usually mixed with gelling additives to improve flow and adhesion properties, which results in high temperatures and long burning times. The fills of incendiary munitions are predominantly non-hydrocarbon materials, such as white phosphorus, thermite, sodium, or certain metals. Most incendiary weapons create fire spontaneously upon exposure to air or intense heat. They are delivered by a wide variety of large- and small-caliber munitions, such as air-delivered bombs, artillery rounds, shoulder-fired rounds, hand and rifle grenades, and mines.

Table 1 shows the agents, burn temperatures and delivery weapon systems for four flame/incendiary weapons. The burning temperature is one of the characteristics of each weapon depending on what kind of agents is used; i.e., hydrocarbon for flame weapons, metals for incendiary weapons and isopropyl nitrate/magnesium for thermobaric weapons. Thermobaric weapons show the highest burning temperature, flame weapons the lowest.

Table 1. Flame/Incendiary Weapons

Category	Agent	Burn Temp. (°C)	Weapon
Flame weapon	Napalm	800	Flame thrower (LPO-50)
	Pyrogel	800 – 1300	Flame thrower
	Gasoline/thicker	200 – 1000	Flame thrower, fire bombs, Molotov cocktail (800)
	Gasoline gel	200 – 1000	
Incendiary weapon	Thermite	3000	Hand grenade
	Magnesium	>2000	Rocket
	Sodium	97.9	Artillery
	WP	1100	Hand grenade, mortar, rocket, Artillery, shoulder-fired Flame Launcher
	RP	1200	Hand grenade, rifle grenade, mortar, artillery
Fuel-air explosives (Thermobaric weapon)	Thermite	3000	Artillery, mortar, rocket, shoulder-fired flame launcher
	Magnesium	>2000	
	Zirconium	>2000	
	Isopropyl nitrate /magnesium	2500	
Fuel flame expedients	elektron sodium	2000 – 3000 97.5	
	Gasoline/thicker	200 – 1000	Flame eliminator, exploding Flame device (fougass)

WP: White Phosphorous

RP: Red Phosphorous

More details for three major flame weapons: flamethrowers, incendiary and thermobaric weapons.

Flamethrowers

Flame weapons (usually flamethrowers) are generally used in the following combat situations: night ambushes, river-crossing operations, combat operations in the forest and urban environments or deep snow and extremely cold conditions. Flamethrowers are used with ambush teams in order to strengthen the points of defense. They are also used against tanks. The flamethrower, the major flame weapon, can be categorized into four groups based on its launching location and method.

A **classic stream-of-burning-liquid flamethrower** consists of two or three fuel tanks, a firing mechanism with a rifle trigger and gun tube, and a fuel-igniting and pressurizing mechanism. The Russian LPO-50, which is used by more countries than any other classic flamethrower, is a good example of these systems. The LPO-50 was the standard flamethrower in former Warsaw Pact countries. The flamethrower can fire

three, 2- to 3- second bursts in 5 to 7 seconds, to a range of 70 meters. It takes approximately 20 seconds for the line of flame to reach the target.

A **shoulder-fired flamethrower** takes advantage of Shoulder-fired Launchers that can deliver rocket-propelled projectiles to much greater distance (400 to 750 meter) than can be done with classic flamethrowers. The rocket-propelled projectiles can be filled with either flame, usually a form of napalm and pyrogel, or incendiary mixtures. Also, compared with classic flamethrowers, rocket-propelled flame rounds give a reduced fire signature, have longer fuel shelf-life, and do not require fuel reloading and field mixing, all of which makes them very easy to operate.

Recent conflicts, like those in Afghanistan, Bosnia, and Chechnya have increased the development of a proliferation of infantry weapon systems designed for urban combat. Improvements in propellants, explosives, and materials have dramatically increased the range and lethality of munitions delivered by shoulder-fired launchers, while at the same time decreasing the weight of these systems. The Russian RPO (infantry rocket flamethrower) is a good example of the types of weapon systems that have resulted from lessons learned by recent conflicts.¹⁶ The RPO, a handheld disposable flamethrower, launches a flame-type projectile for a distance of up to 400 meters. This weapon was designed to replace the LPO-50 and therefore is probably found in many former Warsaw Pact and Former Soviet Union (FSU) countries. The RPO-Z, the follow-on model to the RPO, is a complete disposable single-shot system. It has an enhanced effective range of 600 meters and a maximum range of 800-1200 meters.

The ATO-200 is a combination **tank flamethrower**. It has a maximum range of 200 meters and can fire seven shots per minute. However, when heavy fire in a given area of the zone is required, ATO-200 can release all its fuel in one shot.

TPO-50 is a **heavy infantry flamethrower** that consists of three identical piston-operated cylindrical flamethrowers mounted on a two-wheeled cart. Each flamethrower assembly has folding front and rear sights and may be elevated between 2° and 50° giving a maximum range of 180 meters.

Table 2. Flamethrowers

Category	Distance	Description
LPO-50 (classic)	40-70	2- to 3- second burst in 5 to 7 seconds
RPO (shoulder-fired)	400-700	Handheld and disposable
ATO (tank launcher)	200	7 shots/min
TPO (heavy infantry)	180	Mounted on a two-wheeled cart

The threat from classic flamethrowers will gradually be decreased, but not diminished, and be augmented by the increasing threat from longer-range, shoulder-fired launchers that fire a variety of flame, incendiary, and incendiary/blast rounds.¹⁶ Systems with greater stand-off ranges (such as the Russian Shmel flamethrower, a disposable, shoulder-fired launcher that fires incendiary, thermobaric (incendiary/blast), and smoke rounds to an effective range of 600 meters) are likely candidates for replacement of

shorter range flame/incendiary weapon system. Newly-developed thermobaric rounds for existing RPOs will proliferate over the next 10 years and become a significant threat to the soldier system by the year 2009.¹⁶

The war in Afghanistan proved that a new type of flame weapon, one with greater range and better effectiveness against heavily fortified strong-points, was needed. Thus, the Soviets developed and fielded the RPO. The first RPOs launched a projectile with an incendiary warhead out to 400 meters. The RPO-A, also known as Shmel (literally Bumblebee, the Russian nickname for the RPO-A), was developed by the Soviets in the early 1980s as an improvement to the RPO. It was more effective than the original RPO in defeating Afghanistan forces located in buildings or defiled by mountainous terrain.

Incendiary Weapons

Incendiary weapons have their special niche on the battlefield and will pose a threat to the soldier system throughout its life cycle. White phosphorous (WP) artillery rounds likely pose the greatest near-term threat to the Soldier System.

Based on the vulnerability of targets, incendiary weapons can be grouped into four broad categories: metal incendiaries, pyrotechnic incendiaries, pyrophoric incendiaries, and oil-based flame and incendiary agents. Of the four categories, all but the pyrotechnic incendiaries derive their oxygen from the air; pyrotechnics incorporate their own oxidizing agents.

Many metals in metal incendiaries react readily with oxygen or air, creating heat in the process. At high enough temperatures, some react so violently that they burst into flames. Pyrotechnic Incendiary agents are ignitable mixtures comprising a fuel and an oxidizing agent. They therefore incorporate their own source of oxygen and do not rely on the surrounding air for combustion. The mixture of an oxidizing agent and an inflammable material accelerates its rate of combustion and increases its burning temperature. Pyrophoric Incendiary agents are materials that ignite spontaneously when exposed to air. This property does not need special igniters. Pyrophoric incendiary agents are used alone or with other flame/incendiary agents. Oil-based Flame and Incendiary Agents, hydrocarbons derived from petroleum oil, are inflammable liquids that have a high combustion heat and produce a large flame. Because they are relatively cheap and widely available, they have long been used as flame agents.

A flame/incendiary may also be classified either as an intensive type or as a scatter type. The intensive agents are designed for use against materials and buildings or low combustibility. For this purpose, it is necessary that they burn at a very high temperature and that their fire be held in a compact mass. Intensive agents include the metal and the pyrotechnic incendiaries. The scatter-type agents are designed for use against readily combustible targets, or as direct casualty agents against people; such targets do not require intense point-sources of fire and heat. These targets can be damaged if relatively small quantities of burning flame/incendiary agents are scattered over their surfaces

Table 3. Incendiary Agents and Types

	Intensive type	Scatter type
Metal Incendiaries	X	
Pyrotechnic Incendiaries	X	
Pyrophoric Incendiaries		X
Oil-based Incendiaries		X

Pyrophoric and oil-based flame/incendiaries are examples of scatter agents. Their destructiveness is greatest when they are sufficiently adhesive enough to cling to surfaces while burning, and adhesion-improving additives have been developed for them.

Fuel Air Explosive (FAE, Thermobarics)

Fuel Air explosives (FAEs) are primarily blast-effect weapons, although the thermal effects are substantial and may contribute to secondary or tertiary damage to dismounted soldier.¹⁵ FAEs generate alternating waves of positive and negative pressure. Non-living targets are destroyed or damaged by the initial positive overpressure, but the subsequent negative under pressure is most lethal to live targets, at it causes blood vessels in the lungs to rupture. FAE munitions are warheads filled with highly combustible fuels. The total energy of FAE explosion is approximately five times that of a conventional high explosive (HE). This difference exists because in FAE combustion, atmospheric oxygen contributes to the detonation, whereas in a conventional HE explosion, the available energy comes from the breaking and recombining of the bonds in the explosive molecules. FAE munitions are most effective against soft targets and open-air targets.⁹ Thermobaric weapons (volumetric weapons) use slurry of liquid (Isopropyl nitrate) and metal (magnesium or aluminum). Interior blast from multiple reflections is the most promising use and the most dangerous threat. For this weapon, thermal effects are moderate.

An enemy in any battlefield situation could use the above flame/incendiary weapons. In some specific combat situations, a weapon is more favorable than the other in power, capability, and function. The following chapter shows one of the bases of the weapon selection for four different levels of conflicts and three different warriors.

Chapter 4

Flame/Thermal Battlefield Operations

a. Dismounted

The flame/thermal threats to dismounted warriors vary immensely. This variation is derived from the tactical disposition of troops, the logistic condition, the order of battle, the time of day, the length of encounter, etc. Therefore, it is hard to predict what kind of threats soldiers are going to be exposed to. No assessment would be representative and definitive for this wide range of open flame/thermal circumstances.

Flame/thermal protection for the dismounted soldier has been identified as a deficiency within the U.S. Army. To determine the flame/thermal threat to the

dismounted soldier, FY 1996-2000 was used as a time frame. And the dismounted soldier system in a flame/thermal environment was depicted by using the following four hypothetical conflicts of varying intensities and technological capabilities: low-intensity conflict/low technology ability (LIC/LTA), low-intensity conflict/medium technology ability (LIC/MTA), medium-intensity conflict/medium technology ability (MIC/MTA), and medium-intensity conflict/high technology ability (MIC/HTA)¹⁶ (See **Appendix A**).

For soldiers in the open field, the real threat is by sudden explosive situations such as liquid gas fireballs or weapon discharges. These high-energy short duration events contain large amounts of thermal energy, which will produce burns to all unprotected areas. Unless the clothing system is flame retardant, the clothing will ignite and produce secondary burning to other body parts.

b. Mounted

In modern warfare, combat vehicles play an increasingly important role. This increase in mobility brings also new increased threats to combat soldiers. If weapon discharge leads to secondary fires, mounted soldiers are now trapped in a small compartment and escape has to be taken into account. Smoke, irritants and toxic products of combustion become a serious problem in confined spaces.¹⁰

Flame and incendiary weapons also damage combat equipment. For example, when napalm is splashed onto a tank, the combustible material on the surface of the tank may catch fire, rubber on the tracks and road wheels may ignite, exposed hydraulic hoses may rupture, and engine compartments may be damaged. Napalm also can ignite exterior-mounted ammunition, which may then cause secondary blast or fragmentation damage when it cooks off. This secondary blast or fire can be a serious threat to mounted soldiers

From the actual battlefield environment, it has been shown that issuing flame protective clothing to soldiers has reduced the level of burn injuries. The evidence collected indicates that once a tank begins to burn, the heat generated is enough to burn unprotected areas of the body but flame retardant clothing provides enough protection to allow personnel to escape from the burning vehicle.

c. Military Operations in Urban Terrain (MOUT)

In urban fighting, incendiary agents and flame-throwers are often used to destroy facilities and concealed personnel. Because of their signature, flame-throwers are not always useful for night fighting. Heavy snowfall and low temperatures also degrade their effectiveness. Because ground-based flame weapons are short-range weapon systems, users require cover and concealment while approaching a target. Therefore, desert or wide-open areas may not be favorable for the employment of ground-based flame-throwers.¹⁰

Flame weapons used during combat operations in the forest and urban environments are most likely to cause burn injury to enemy personnel concealed in the forest and buildings or any other defensive installations.

The greatest threat from flame/incendiary weapons occurs during defensive or urban fighting. The threat from classic flamethrowers will gradually diminish and be augmented by the increasing threat from the longer-range, shoulder-fired launcher that fires incendiary, thermobaric (incendiary/blast), and smoke rounds to an effective range

of 600meters. Newly-developed thermobaric rounds for existing RPGs will proliferate over the next 10 years and become a significant threat to the Soldier System by the year 2009.⁹

Flame/incendiary weapons could be the most catastrophic threats to the soldiers, dismounted or mounted, operating in combat situations.

Chapter 5

Flame/Thermal Hazards

a. Burn Injury Hazards

A hazard is defined as an individual risk of casualty when exposed to a threat. Military combatants can suffer burn injuries from variety of sources to include hydrocarbon fires, chemical burns from flame/incendiary agents, flash fires, nuclear fireball or flash, radiation, inhalation of hot gases, clothing ignition, electrical or periphery combustion.²⁴ This study is focused on flame burn hazard that can be controlled by the use of protective clothing systems. Other hazards possible from battlefield threats such as explosion, shock, unconsciousness, direct hit, asphyxiation, smoke, and scalding from hot plate or steam are excluded. Flame/thermal burn injury hazards can be separated into two categories, threat generated burn and incidental burn hazards. This classification fits the combat and non-combat situation of individual soldiers on the battlefield.

Threat Generated Burn Hazards

This refers to flame/thermal hazards generated from battlefield threats, mostly flame/incendiary weapons, that can cause burn injury. These hazards are from burning of the agents or fuel used for flame/incendiary weapon.

A flame/incendiary agent is either a single compound or a mixture of chemicals that can be triggered into undergoing a chemical reaction that liberates a large and sustained quantity of heat. Almost invariably the reaction is combustion; i.e., a reaction of a fuel and oxygen. To be effective as a flame/incendiary agent, a composition must have a high heat of combustion that is sufficient thermal energy to damage or ignite its target. Moreover, the rate at which this heat is liberated must be neither too fast nor too slow so the net heat remains long enough to cause damage. The generation of large flames by a flame/incendiary agent and, in most cases, a high burning temperature facilitates the transfer of heat between the incendiary agent and its target.

Flame weapons use predominantly hydrocarbon fills such as napalm, pyrogel, or gasoline. Petroleum-based flame agents possess high-combustion heat (10,000 cal/g), produce a large flame, and often generate large amount of carbon monoxide. Easily ignited hydrocarbons, such as gasoline, burn so rapidly that, when dispensed by a propellant charge, they are consumed in one large and relatively harmless flash. For this reason gasoline, when used as a flame agent, is mixed with certain additives that greatly increase its destructiveness. They modify its flow properties into a form more suitable to weapon use and make it sufficiently adhesive and cohesive to stick to surfaces of burning objects. They may also prolong its burning time and increase its burning temperature.

The fills of incendiary weapons are dominantly non-hydrocarbon, such as white phosphorous(WP), red phosphorus (RP), thermite, sodium, and certain metals, that create fire spontaneously upon exposure to air or intense heat. Most incendiary weapons create fire spontaneously upon exposure to air or intense heat.

Incidental Burn Hazards

In the case of incidental flame burns, there is very little difference between military and civilian burn. The major incidental flame/thermal burn hazards are petroleum, oils, and lubricants (POLs) that are also frequently used in civilian life. The location of incidental burn injury is usually at field kitchen, fuel deposit, and buildings. Burn injury data show that accident is the most frequent burn injuries in the Army. And more burns were from liquid scalds than flame by food service specialists.²¹ The major fuels used in the military operations are JP-8, diesel, and gasoline.[**Appendix D**] Fire from fuel leaks, stack red-hot, and spark emission, are frequent causes of accidental burn injuries in the Army. The primary fuel for Army field space heater and cooking burner is the mixture of JP-8 (90%) and diesel (10%). The current gasoline operated space heater (Yukon stove) and M2 cooking burner will be replaced with new heater/burner using JP-8 and diesel in the next two years.

The following table shows threat generated and incidental burn hazards identified by three different categories of soldiers operating on the battlefields.

Table 4. Flame/Thermal Burn Hazards Identified on the Battlefield

Battlefield Soldiers		Flame/thermal Hazards
Dismounted	Threat generated	Fire from enemy weapons (gasoline, pyrogel. Napalm, WP, Isopropyl nitrate)
	Incidental	Fuel fire(JP-8, diesel, gasoline) at shelters, field-kitchen, and fuel depository, burning trash pits, flares or pyrotechnics
Mounted (Tanker)	Threat generated	Fire from enemy weapons (gasoline, pyrogel. Napalm, WP, Isopropyl nitrate)
	Incidental	Large and small caliber ammunition [Appendix C] and smoke grenades, fuel (JP-8 and DF2), hydraulic fluid, transmission oils
Mounted (Aviator)	Threat generated	Fire from enemy weapons (vital)
	Incidental	Secondary fire from crash, fuel fire (JP-8, and JET A) during refueling
MOUT	Threat generated	Fire from enemy weapons (gasoline, pyrogel. Napalm, WP, Isopropyl nitrate)
	Incidental	Structural fire (building fire), fuel fire

Chapter 6

Fire Characteristics

There is an infinite number of fire scenarios possible on the battlefield. Even for the battlefield burn injury hazards, there are so many flame/thermal patterns possible from different fuels and burning environments. Fire characteristics are one of the ways to categorize them in a few groups. Pool fire, spray fire and structural fire, are the fire characteristics recognized for battlefield flame/thermal burn injury hazards.

a. Pool Fire: Pool fires are divided into two major classifications, confined and unconfined. Unconfined pool fires exist in areas where the formation of circular pools will not be impeded by barriers such as walls, dykes and drains. Confined pool fires are pool fires that can not spread in an unobstructed manner. Both of these configurations are possible on the battlefield. Unconfined pool fires are characteristics of those resulting from such open field fire incidents as flame/incendiary weapons and aircraft crash or refueling accidents. Fuel sources range from very low flash point flammable liquids such as Kerosene and Jet fuels (JP-4,5, and 8) to very high flash point liquid such as lubricating oils.¹⁷

Most hydrocarbon fuel fires become optically thick when the diameter is about 3m or larger. Under these conditions, the maximum emissive power that has been measured for gasoline fires is in the range of 130 kW/m^2 . The measured heat flux appears to decrease for larger fires, indicating that the emissive power is decreasing.⁶

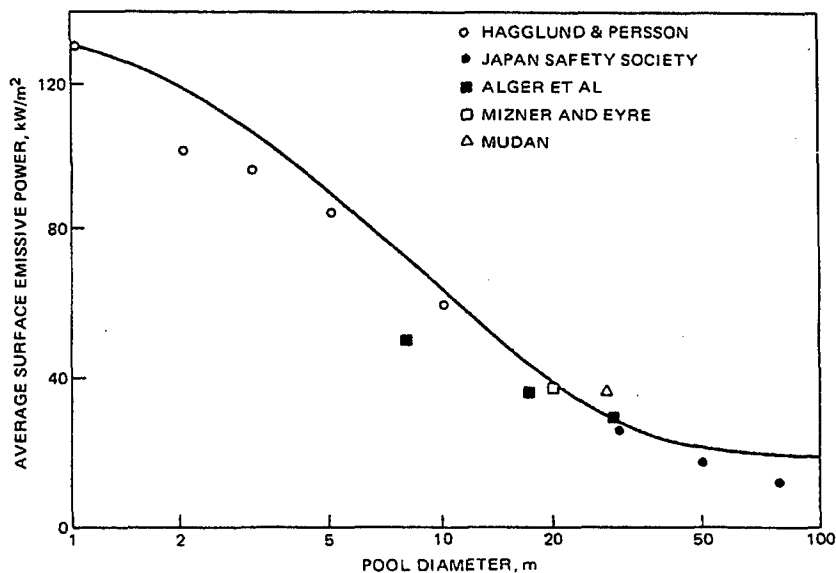


Figure 3. Average Surface Emissive Power for Gasoline, Kerosene, and JP-4 Pool Fires (SFPE Handbook of Fire Protection Engineering)

A modeling work at Worcester Polytechnic Institute (WPI) showed that distance affects not only the magnitude of the radiative flux to a target, but also the distribution of the flux along the plane. If an object is very close to a fire the radiative flux to that object can be very high in some locations and much lower in others. As the target is moved away from the fire, the flux decreases but also the gradient of fluxes throughout the plane becomes much smaller. Simply providing a radiant panel that creates a constant radiant flux will not accurately recreate the actual fire scenario.¹⁷

The hazards created within a compartment are much greater due to the collection of products of combustion and the increased heat flux back to the fuels. The increase in complexity is due to compartment effects on both the heat release rate of the fire, and the environment generated by the fire.

In unenclosed fires, the supply of oxygen is virtually unlimited and the only source of radiative feedback to the fuel is the burning flame. In enclosure fires, the accumulation of products of combustion due to the limited ventilation can significantly reduce the availability of oxygen within the compartment. In addition to the radiation from flame itself, radiative feedback from the accumulated product of combustion gasses as well as hot enclosure surfaces contributes to the heat flux to the fuel surface, resulting in a corresponding increase in fuel pyrolysis.

For modeling, the base case model was a compartment 5 meters by 5 meters in plane with a ceiling height 3 meters. One of the goals of this modeling was to estimate the effect of fire size on the heat flux to the target.

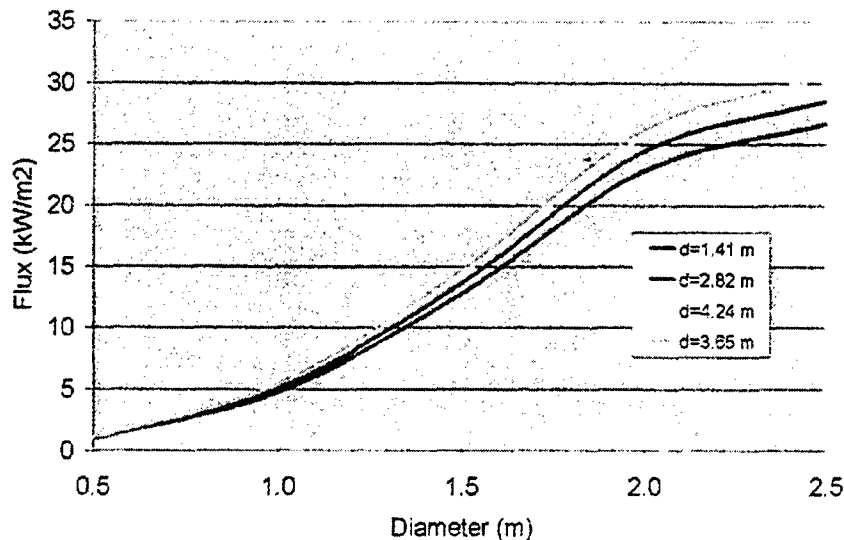


Figure 4. Target Flux vs Fire Diameter

The heat flux to the target is the sum of many different sources other than the actual fire. However, the above figures indicate that the driving force behind the hazardous environment generated by a fire is the fire itself.

It would be expected that vent size would also have an effect on heat flux to the targets. For a given pyrolysis rate there will be a critical vent size below which the fire will be oxygen limited. Figure 5, plotting heat flux to the targets as a function of vertical vent area, shows the critical vent area at 2.0 m^2 .

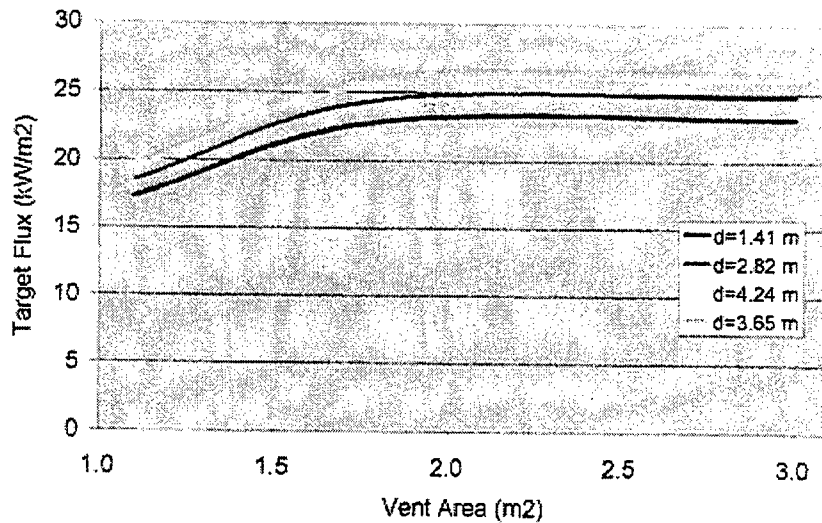


Figure 5. Steady State Target Heat Flux vs Vertical Vent Area

When the target surface was oriented vertically and facing the fire, the maximum possible radiant energy reaches the target. However, the actual target could be oriented differently on the battlefield. Figure 6 shows target heat fluxes for the base case scenario with the face of the targets at a 45-degree angle to the floor. This configuration increases the portion of the heat flux received from the upper layer and the ceiling while decreasing the heat flux received from the wall.

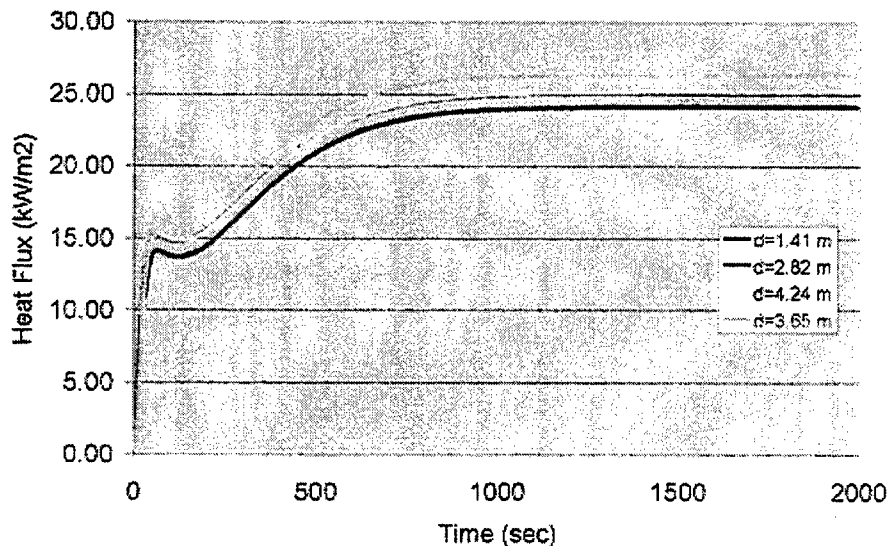


Figure 6. Heat Flux with Target Face at 45° Angle with Compartment Floor

The above figures indicate that the precise orientation of a planer target does not greatly influence the heat flux to the target.

b. Spray Fire

The flames from classic flamethrowers (dismounted) and oil leaks (mounted) belong to this category. The characteristic of spray fire is a result of pressurized fire sources or fuels. Sprayed flame with velocity could hit a target directly. When the adhesive or cohesive fuels hit the protective clothing, the likelihood of survival would be very small. The spray fire reaching other than personnel targets will burn and regress as a pool fire.

c. Structural Fire

Structural fire, including a building fire, is a major hazard to warriors in MOUT situations. This is a big difference between MOUT and other operations. This is a very complicated scenario with many possible variables. The resultant fire might just be the combination of all possible fire characteristics. Table 5 shows the characteristic of fires encountered by warriors on the battlefield.

Pattern example

Table 5. Fire Characteristics for Battlefield Flame/Thermal Burn Injury Hazards

Battlefield Scenario		Fire Environ.	Typical Fire Characteristics
Dismounted	Combat	Open	Jet fire – direct hit of enemy flame weapons (gasoline, napalm, and pyrogel) pool fire - secondary fire from flame weapon
	Non-combat	Open	Pool fire – flash fire from gasoline, diesel, JP Fuels and all other combustible materials (kitchen, fuel depot)
Mounted, Tanker	Combat	Confined/ Open	Confined pool fire – direct hit of flame Weapons, fuel, and ammunition spray fire – high pressure hydraulic oil leaks from damaged pipe line Pool fire – secondary fire (flame weapon)
	Non-combat	Open	Pool fire – flash fire from fuel and other Combustible materials
Mounted, Aviator	Combat	Confined/ Open	Pool fire – flash fire from crashed helicopter (JP-8)
	Non-combat	Open	Pool fire – accidental flash fire during fueling
MOUT	Combat/ Non-combat	Confined/ Open	Pool fire – flash fire from fuels Structural fire (building) – direct hit of Enemy weapons Confined pool fire – fuel and ammunition

No single characteristic represents all possible battlefield flame/thermal situations. But the most considerable fire characteristic common to most battlefield flame/thermal burn injury hazards seems to be a pool fire. Such other fire characteristics as jet fire or spray fire, unless they hit directly, end up with pool fires.

Chapter 7

Heat Flux for a Test

It is a challenging task to choose a heat flux for a flammability test to simulate a wide range of flame/thermal threats or hazards on battlefield. A single heat flux is preferred to a range of heat flux because of its standardization and consistency. There are a couple of requirements to be met for a selected heat flux for a test. First, the heat flux selected would represent the heat intensity of real burn injury hazards to measure the protection of soldiers against those hazards. Second, the heat flux should be within the capacity of the test heater selected. In other words, the selected heat flux will be a basis of selection for the test heater.

As shown in Figure 7, the heat flux for battlefield flame/thermal threats or hazards ranges widely from 0.2 to 10 $\text{cal/cm}^2\text{sec}$ with an infinite number of flame scenarios possible. From a high explosive flame weapon to a small kitchen fire, all different levels of heat flux are possible on the battlefield.

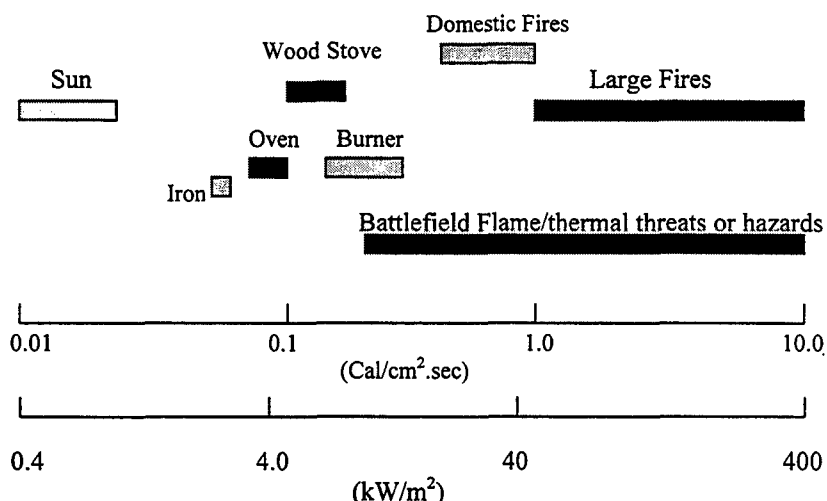


Figure 7. Heat Flux Range for Various Flame/Thermal Incidents

It is well known that each fuel or agent has its own heat of combustion when it

burns. It is possible to estimate heat flux of a fire from a known fuel burning. Table 6 shows heat fluxes for fires from different fuels. Most fuels show a wide range of heat flux.

Table 6. Heat Fluxes for Various Fires

Incidents	Heat flux (kW/m ² [cal/cm ² -s])
Burning propellant (68-91 kg) At a distance of 1.5 m	150 – 250 [3.6 – 6.0]
Projectiles	10 – 4500 [0.25 - 107]
Brush fire (wild)	63 (100) [1.5 (2.4)]
Oil well – flash fire (POL)	84 [2.0]
Flash- over	78.75 [1.9]
Auto gas tank explosion	117.6 [2.8]
Mine explosion, methane	330 [7.8]
JP-4, pool fire	167 – 226 [4.0 - 5.4]
Large fueled fire	90 – 230 [2.1 – 5.8]

A range of heat fluxes is achievable even from a single fuel. It depends on the amount of fuel burning, how it ignites and how fast the fire spreads. The heat flux can be affected by such environmental conditions as wind, humidity and ventilation. Time and distance, however, are the important factors for the characterization of heat flux for the battlefield flame/thermal burn hazards.

a. Time

A fire from a limited amount of fuel is a time process. A flame/thermal burn hazard proceeds along time in three stages: ignition or explosion, secondary fire (flash over), and regress. For example, a flame/incendiary weapon explodes or ignites in the first one-minute period. This stage evolves a large amount of thermal energy and high pressure. This first stage comes usually without any notice or warning. Most warriors exposed to this explosion stage at close distance have rare chance to survive. After a minute, the ignited fuel develops into the next secondary fire stage. All combustible materials around are ignited and burn together. This is the typical characteristic of flash-over or flash fire. When no more combustible materials are available, the fire starts to die off to get into the regression stage.

Figure 3 is a notional graph showing the burning process of four different fuels/agents along time. The heat fluxes plotted on the graph are not experimental data, but estimated values from burning temperature data of flame/incendiary weapons (Table 1). The fuels/agents showing different modes of explosion or ignition reach the same secondary fire stage approximately seven minutes later. This is very important phenomenon of representative battlefield flame/thermal burn hazards.

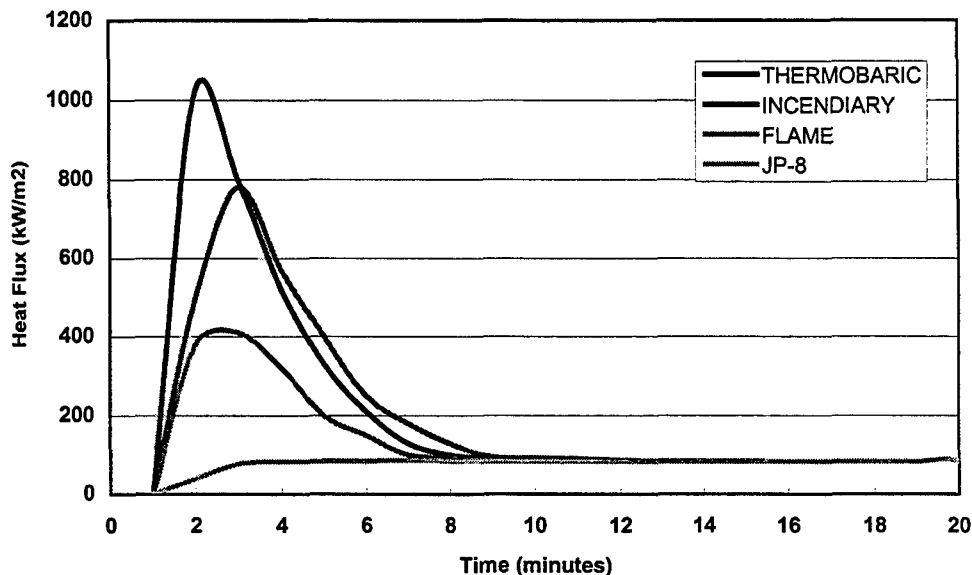


Figure 8. Heat Flux vs Time

The secondary flashover fire is common to most battlefield fuels after their explosion stages.

b. Distance

The distance between a soldier and a fire source or an explosion is another parameter to determine the level of heat flux for a fire. Heat intensity generated from flame/incendiary agents decrease as the distance increases. The further the distance, the safer the soldier. Usually, 20 meters away from the center of a fire source is a safe distance.

When an individual warrior is hit directly by a flame/incendiary weapon, his survivability is very low. In this case, the primary lethality comes from high pressure explosion with high heat flux. The chemical/physical characteristic of the weapon agents can increase the level of burn injury. The burning weapon agent, which is treated with chemicals to be adhesive or coercive, can easily stick to protective clothing surface and it is almost impossible to escape from the burning clothing without severe burn injury. In this situation, the distance ($d = 0.0$) is too close to protect an individual soldier using a protective garment. The UK provides a finish to clothing to allow substances to slide off or be more easily brushed off.

The useful data available on real thermal challenges are very limited and only propellant fires and incendiary explosions are covered in any depth. Useful data from

other thermal challenges are scarce and most data available are only post incident (i.e. bomb blasts, large fires etc.).

The heat flux for the ignited Naval propellant MNLF2P was measured experimentally at different distances from the central point. The result was fit to the following equation¹⁹.

$$HD = \frac{27.1m}{R^{1.68}}$$

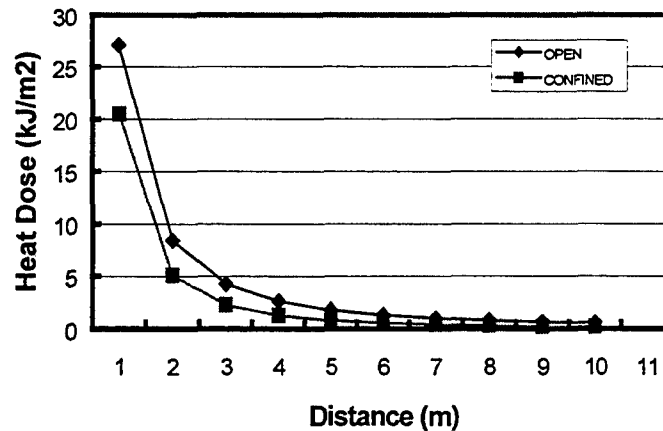
Where HD = Heat Dose (kJ/m²),
m = mass of propellant (kg), and
R = Radius (m)

Inside a compartment, the equation changes as follows:

$$HD = \frac{20.5m}{Y^2}$$

Where Y = Displacement from propellant (m)

The above two equations plotted on Figure 9 show how heat fluxes decrease with increased distance. The heat flux reduced faster inside a compartment than outside. This may be due to the limited oxygen amount inside the compartment required for continuous combustion.



**Figure 9. Heat Dose vs Distance
(per kg of Propellant)**

The heat fluxes reach peak values within one minute after ignition at set distance from the propellant. All of these values decrease rapidly, reaching equilibrium within 2 to 3 minutes. Peak heat fluxes measured at a distance of 1.5 m from the burning propellant were in the range of 150 – 250 kW/m² for 68-91 kg of propellant. These heat flux values are more than sufficient to ignite such materials as wood, paper, and rags. However, those materials could not burn until fresh air was drawn into the space. For the materials, this corresponds to an oxygen concentration of 15%. The oxygen concentration high in the compartment rapidly dropped to about 2% and did not get back above 15% until 7 minutes into the burns. This explains the difficulty in sustaining burning of the materials inside a compartment.¹⁹

The troop safety line for incendiary fire support would be the same as for regular HE weapons. The safety distance from mortar and artillery fire is 400 meters for infantry soldiers in a dismounted assault and 200 meters when mounted. For "friendly" grenade burst it is 300 meters for dismounted and 200 meters for mounted infantry.¹⁰

c. Trade-off Analysis

So many different fuels and agents exist on the battlefield and even the heat flux from a single fuel or agent burning varies with time and distance. Strictly speaking, there is no single heat flux representing the heat intensity of various battlefield burn injury hazards. Any heat flux selected for a flammability test would stand for just one of many possible flame/thermal situations on the battlefield.

The level of target protection can be determined by trade-off. The maximum protection can be expected by selecting the highest value of heat flux covering battlefield burn injury hazards. In this case, soldier-uniform protection could be maximized. Other important factors such as cost, weight, and comfort will be traded off.

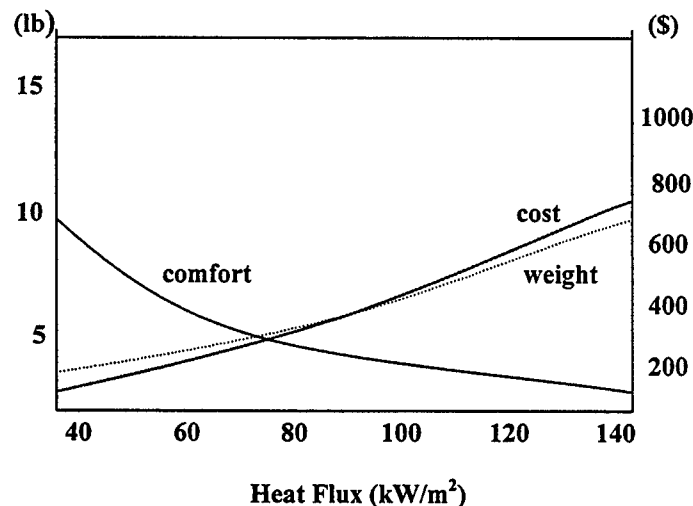


Figure 10. Trade-off Analysis

Figure 10 shows how the weight and cost of protective clothing ensembles go up

as the target heat flux increases. The increase of the target heat flux from 84 to 100 kW/m² will increase the cost and weight by 50 percent. One of the requirements for our current DTO project is reducing the cost of current protective clothing for Army mounted soldiers by 50%. Weight is critical to the mobility of individual soldiers operating in the battlefield. The key is how to maximize the protection with reasonable cost and weight increased. The weights and costs of five configurations of current military protective clothing systems are calculated from the sum of the cost of components of each configuration [Appendix B].

These are the differences between military flame/thermal protective clothing and civilian firefighter protective clothing. The firemen's protective clothing needs insulation good for a long time to fight with a fire. Their weight and cost are not as important as the military. The military protective clothing protects individual soldier escaping from flame/thermal burn hazards in a very short time. High mobility with lightweight is a crucial requirement.

Currently, the U.S. Army Armor Center insists on 2.4 cal/cm²-sec instead of 2.0 cal/cm²-sec as a test heat intensity simulating flame/thermal hazards inside combat vehicles. Center scientists believe that a higher heat flux could result from the accumulation of heat inside an armored vehicle on fire.

A single heat flux selected for a test will represent not only battlefield burn injury hazards, but also the level of target protection adopted for specific user groups.

Chapter 8

Thermal Performance Criteria for Military Protective Clothing System

There is a need for thermal performance criteria to evaluate the protective performance of military clothing worn by soldiers exposed to battlefield burn injury hazards. These criteria will be the basis of selection or rating of new or existing flame retardant clothing fabrics on a flammability test. Being able to test on a newly developing bench-scale test apparatus is one of the requirements for the criteria

Three major elements of the criteria are heat flux, exposure time, and the amount of burn injury. Heat flux for a test has already been discussed in Chapter 7. The exposure time and the percentage of burn injury will be determined based on battlefield operational situations.

a. Heat Flux

A flash fire of gasoline, JP fuels or Petroleum/oil/lubrication (POL), with pool fire characteristic is the most treacherous burn injury hazard in common with various battlefield flame/thermal situations. The heat flux of 2.0 cal/cm²-sec is for the fires.²² At this time, all other hazards such as explosion, direct hit, and smoke are eliminated from our consideration because they are beyond flame/thermal protection.

In case of most flame/incendiary weapons, they differ in the first ignition and explosion stage, but are alike in the secondary fire stage. Regardless of the kind of fuel and weapon systems, flame is a secondary threat or hazard.

This is the reason why most flammability tests use the heat flux of $2.0 \text{ cal/cm}^2\text{sec}$ as the intensity of the heat source (See Table 7).

Table 7. Heat Flux and Exposure Time for Current Flammability Tests

Tests	Heat Flux (kW/m ² (cal/cm ² .sec))	Escape time (sec)
TPP (ASTM D4108) Quartz/Meker	84.0 (2.0)	-
(ASTM D13-77-4) Meker	84.0 (2.0)	-
NC State (full-scale) Burner	84.0 (2.0)	3 – 4
FTMS 191, vertical flammability	Open flame	-
ISO 6942	Max. 80.0 (1.9)	-
EN 367 Heat transfer(flame)	80.0 (1.9)	-
USAARL (Burnsim)	128.9 (3.07)	5
USA Armor Center	100.8 (2.4)	6
US navy Shipboard	100 – 105(2.0 – 2.5)	2
	84.0 (2.0)	6
USMC	84.0 (2.0)	2
US Air Force	84.0 (2.0)	3 – 5

Mounted soldiers operating in an enclosed space such as tankers or Army aviators are exposed to higher heat flux. U.S. Army Aeromedical Research Laboratory (USAARL) employs the high heat flux of 3.07 to simulate a pool fire of JP-8, but their work is to evaluate their burn simulation program for research use only.

b. Exposure Time

In a battlefield flame/thermal situation, there is a time period during which an individual soldier must escape from flame/thermal hazards without severe burn injury. Flame protective clothing performance helps provide some escape time and reduce the level of burn injury. Flame protective clothing performance helps provide some escape time and reduce the level of burn injury. This escape time concept is applied to a flammability test as an exposure time to a test heat source. The exposure time, how long human skin is exposed to a test heat flux, decides total energy absorbed by human skin during the time period. And the total energy absorbed by human skin is a major parameter in measuring burn injury.

There are some differences in exposure time requirement between military and civilian fire scenarios. In the case of civilian fires, the fire itself is the only enemy against whom firemen are allowed to concentrate on fighting without any interruptions until it is extinguished. Contrary to civilian cases, the most catastrophic flame/thermal threat in the battlefield is enemy's flame/incendiary weapon. However, this threat is just one of many threats encountered on the battlefield, such as chemical/biological and ballistic threats. Surviving those threats is to meet, fight and win over real enemy. This

is why combat soldiers on the battlefield never try to fight flame/thermal hazards down, but rather escape from them as soon as possible.

Flame protection requirements originated from the aviation community in the U.S. Army. In 1996, the U.S. Army protection or escape time was **10 seconds**. This 10 seconds requirement was based on total escape time from exit of the burning vehicle to exit of the flame area. It includes the ground egress time for aviators to unbuckle their belt, get out of the seat, exit the helicopter, and flame area.

In case of combat vehicle crewmen such as tankers, they must egress from their screw station in 10 – 15 seconds and the entire crew must be out of the vehicle in 20 seconds.¹⁰ Critical point is that the crew and individual crewman only need to be out of the harm of the flame – not to the ground. This is critical in determining when to stop the clock during testing. The crewman can get his body – including his feet and legs - out of the hatch and atop of the turret to be considered out of the vehicle.”

The U.S. Air Force requirement is **3 seconds**. And their concern is the flash-fire, especially during refueling of fighter planes. In a flash-fire condition, there is a pre-flash build-up period of the fuel source in a vaporizing state. Liquid fuel must vaporize to burn. The flash fire ignites and will burn for a very short time without a continuous feed, estimated from **one to five seconds**, depending on the fuel source.

The Navy requirement is **3 seconds** based on the theory that a man running could escape from a 30-50 foot radius of flame area if he was moving at 10-17 feet per second. The requirement is based on how long it takes to carry a dummy from the average fuel spill pool on the deck of a carrier.²⁴

Table 8. Escape Time for Current Military Operations

	Escape Time (second)	Basis	Total exposure (cal/cm²) at 2 cal/cm².s
Army Aviators	10 (6)	Ground egress time to unbuckle belt, get out of seat and exit the flame area	20 (12)
Air Force	3-5	Flash-fire, especially during hot-refueling of fighter planes	6 – 10
Navy	3	For a running man (10-17 ft/sec) escaping from a 30-50 feet radius of flame area	6

Most current fabric flammability tests are equipped with a shutter to control precisely the duration of the exposure of the fabric. This water-cooled, pneumatic shutter can be opened or closed in less than 0.2 seconds. Sometimes an automated mechanical shutter is used for more precise control of the exposure time.

c. Percentage of Burn Injury

In case of the warrior, the surviving chance will be higher than 50% chance of surviving for civilians⁶ for the same percentage of burn injury. This will be one of very practical criteria for evacuating or transferring victims to a burn center due to the inability to replace significant body fluid losses on the battlefield.²⁴ The maximum 20% total 2nd/3rd degree body burn requirement is well accepted by most users. The Armor center uses "no greater than a 1st degree burn" based on the assumption that the vehicle utilizes a functioning state-of-the-art fire detection/suppression system. The center accepts 20% total 2nd/3rd degree body burn requirement without fire protection systems which can happen if the system malfunctions or is made inoperable in combat.

d. Recommendation

Based on the result of this study, the heat flux of 2.0 cal/cm²-sec is recommended for flame/thermal protection testing against most battlefield burn injury hazards. Mounted soldiers such as tankers and aviators are considered to be exposed to more intense heat sources in confined spaces than dismounted soldiers. The Armor center has requested the use of 2.4 cal/cm²-sec as a test heat flux to measure the protection of tankers. Fortunately this specific heat flux is available on the new bench-scale test apparatus. Our recommendation would be a combination of the advantages of currently available test methods, rather than selecting one over the other, to optimize the measurement of protection performance of military clothing system. Four test methods including the new developing one are compared in Table 9.

Table 9. Comparison of Current Flammability Test Methods

Characteristic	Thermal Protective Performance	Flame resistance Of clothing, Vertical	PyroMan Full-scale Test	FMRC Flammability test Apparatus
Standards	NFPA 1971 (TPP)	FTMS 191A	ASTM F1930-99	
Ignition Source	2 Meker or Fisher 9 Quartz IR tubes	1.5" tirrill/bunsen	8 propane burners	7.6x25.4 cm IR Radiant
Heat flux	2cal/cm ² -sec	Open flame	2cal/cm ² -sec	Up to 3cal/cm ² -sec
Heat Sensors	Copper disk calorimeter	None	Skin simulating Heat sensor	Skin simulating sensor
Sample size	Fabric (100 x 100 cm)	Fabric (7.6 x 30.5 cm)	Clothing Ensemble	Fabric (7 x 5 inches)
Sample Orientation	Horizontal	Vertical	Dressed manikin	Horizontal/vertical
Properties measured	Heat energy transmitted through the fabric to thermocouples	Char length After-flame time Afterglow time	Heat transmitted to each sensor location on the surface of an manikin	Heat energy transferred through the fabrics to skin simulating sensors
Burn injury Assessment	Yes	No	Yes	Yes
% of Burn injury	No	No	Yes	Exposure time correlation
Locations of burn injury	No	No	Yes	Air gap correlation

Two of the most popular bench-scale fabric tests, thermal Protective Performance (TPP) and vertical flame test, are recommended for primary rating or selecting of flame-retardant fabrics to take their advantages of simple test procedure and inexpensive cost. The only full-scale clothing test, PyroMan, will be used continuously to get valuable performance information such as the location and the amount of burn injury that are not available on any other tests. This test will also provide valuable information of exposure time recommended for each configuration of protective clothing ensemble. Those standard tests are well accepted for the evaluation of flame-retardant fabrics.

New developing FMRC apparatus has advantages of each other test methods. This bench-scale test has the capability of burn injury assessment using a skin simulating sensor that is superior to a copper calorimeter in detecting the effect of clothing on skin cooling. The maximum heat flux of $3.0 \text{ cal/cm}^2\text{sec}$ on this apparatus makes testing possible at any heat flux between 2.0 and $3.0 \text{ cal/cm}^2\text{sec}$. The Armor Center insists on a higher heat flux of $2.4 \text{ cal/cm}^2\text{sec}$ as a test heat source to simulate the accumulation of heat inside a confined space of combat vehicles. This is a big advantage over TPP and PyroMan. For example, burn injury at $2.4 \text{ cal/cm}^2\text{sec}$ can be estimated on this apparatus by correlating with PyroMan test data. The new bench-scale apparatus not only covers the disadvantage of other test methods, but also correlates them to get more reliable results.

The combination of the above four tests will form the complement to the limitations of current test methods. And the recommended heat flux and exposure time for the recommended percentage of burn injury is much more flexible and feasible on testing.

Chapter 9

Conclusions

One of the major parameters for a new flammability test is heat intensity. The heat intensity, usually expressed in heat flux, should simulate the heat flux of flame/thermal burn injury hazards on the battlefield. The dilemma is how to select a single or range of heat flux representing various battlefield flame/thermal hazards. This study shows the rationale of the selection of a heat flux for the new flammability test. Flame/thermal threats in the battlefield have been reviewed for dismounted and mounted warrior in battlefield operations, and flame/thermal burn hazards have been reevaluated for both threat generated and incidental cases.

First, this study is focused on flame/thermal burn hazards that are the hazards against which the protection can be improved using protective clothing system. Other flame hazards such as explosion, smoke, and direct hit, are excluded from this study.

Next, the infinite number of possible flame/thermal scenarios was expressed as a few representative fire models such as pool fire, spray fire, and structural fire. The effect of fire diameter, distances, vent area, and target orientation on the representative fires was examined using a computer modeling study.

Finally, thermal performance criteria for military protective clothing were recommended for users. No second-degree burn injury at the heat flux of secondary flashover ($2.0 \text{ cal/cm}^2\text{sec}$) for 6 second was recommended.

In the future, the correlation of the amount of burn injury and exposure time; and the location of burn injury and air gap is required to enhance the capability of a bench-scale test providing valuable information currently available only from a full-scale test.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-~~00105L~~ in a series of reports approved for publication.

This page intentionally left blank

APPENDIX A

Flame Weapons for Different Conflict Intensity and Technology Ability

Appendix A

LIC/LTA (Low Intensity Conflict/Low Technology Ability)

Nomenclature	Fuel	Burn Temp(°C)	Effective range		Maximum range	
			Thickened	Unthickened	Thickened	Unthickened
T-148/B flamethrowers	Gasoline/napalm gel	200-1000	50m	20m	80m	32m
LPO-50 flamethrowers	Napalm	800	40-50m	15-20m	50-70m	20-28m
Molotov cocktails	Gasoline/thickeners	200-400	N/A	N/A	N/A	N/A
Fire bomb	Gasoline/thickeners	200-400	N/A	N/A	N/A	N/A
Flame field expedients	Gasoline/thickeners	200-400	N/A	N/A	N/A	N/A

LIC/MTA (Low Intensity Conflict/Medium Technology Ability)

Nomenclature	Fuel	Burn Temp(°C)	Effective range		Maximum range	
			Thickened	Unthickened	Thickened	Unthickened
RPO flamethrowers	Pyrogel	800-1300	190-200m	N/A	400 m	N/A
LPO-50 flamethrowers	Napalm	800	40-50m	15-20m	50-70m	20-28m
Hand made flamethrowers	Gasoline/thickeners	200-1000	20m	8m	30m	12m
Homemade rockets	Gasoline/Thickeners	200-1000	N/A	N/A	2000m	2000m

MIC/MTA (Medium Intensity Conflict/Medium Technology Ability)

Nomenclature	Fuel	Burn Temp(°C)	Effective range		Maximum range	
			Thickened	Unthickened	Thickened	Unthickened
RPO flamethrowers	Pyrogel	800-1300	190-200m	N/A	400 m	N/A
LPO-50 flamethrowers	Napalm	800	40-50m	15-20m	50-70m	20-28m
TPO50	Petroleum/thickeners	800-1000	180m	70m	270m	100m
ATO-200	Petroleum/Thickeners	800-1000	130m	50m	200m	800m

MIC/HTA (Medium Intensity Conflict/High Technology Ability)

Nomenclature	Fuel	Burn Temp(°C)	Effective range		Maximum range	
			Thickened	Unthickened	Thickened	Unthickened
M931-7 manportable	Thickened/liquid fuel	200-1000	40-50m	20-25m	67 m	30m
LPO-50 manportable	Napalm	800	40-50m	15-20m	50-70m	20-28m
T-148B manportable	Gasoline/napalm gel	200-400	50m	20m	80m	32m
RPO disposable	Pyrogel	800-1000	190-200m	N/A	200-400m	N/A
Calid NR 179 disposable	RP	1300	8-80m	N/A	80m ¹	N/A
HAFLA-35L DM34 disposable	RP/powder aluminum	1300	8-80m	N/A	80m ²	N/A
ATO-200 tank-mounted	Petroleum/Thickener	800-1000	130m	52m	200m	80m
TPO-50 cart-mounted	Petroleum/Thickener	800-1000	180m	65m	200m	80m

¹ The projectile will burst 2 seconds (70-80 meters) after leaving the launcher.

² The projectile will burst after having traveled unhindered 70-80 meters in flight (approximately 2 seconds)

This page intentionally left blank

APPENDIX B

Weight and cost of Current Military Protective Clothing System

Appendix B

Item	Weight (lb)	Cost (US\$)
T shirt	0.17	1.85
Briefs	0.13	1.65
Cotton underwear	1.64	16.47
Nomex underwear	1.20	44.05
Coat & Trousers, Aircrew	2.50	179.45
CVC coverall	2.75	179.20
Overalls, Bib	4.60	190.05
Jacket, CW, CVC	2.31	126.25
Jacket, CW, Aircrew w/ Liner	2.31	260.60

Configuration number		Weight (lb)	Cost (US\$)
1	Aviator	2.80	181.10
	Tanker	3.05	182.70
2	Aviator	4.14	195.92
	Tanker	4.39	195.67
3	Aviator	3.70	223.50
	Tanker	3.95	223.25
4	Aviator	6.01	484.10
	Tanker	6.26	349.50
5	Aviator	10.61	674.15
	Tanker	10.86	539.55

APPENDIX C

Ammunition Carried Inside Combat Vehicles and Tanks

Appendix C

KE(120mm):	M 829, M829A1, M829A2, M829E3
KE(Training):	M865A1, M865E2, M865E3, LRKE (Tnr)
CE(120mm):	M830, M830A1
CE(Training):	M831, M831A1, (MPAT Tnr)
KE(105mm):	M833, M900
CE(105mm):	M456A2

APPENDIX D

Thermophysical Properties of Fuels Used on the Battlefield

Appendix D

Asymptotic Burning Rate (g/m ² .sec)	35.0	55.0	51.0	39.0	39.0
Effective Absorption Coefficient (1/m)	1.7	2.1	3.6	0.8	0.7
Chemical Combustion Efficiency	0.9	0.92	0.9	0.9	0.84
Convective Fraction	0.6	0.61	0.6	0.6	0.56
Radiative Fraction	0.3	0.31	0.3	0.3	0.28
Density (kg/m ³)	940	740	760	750	760

JP-8

Gravity (°API)	45.6
Density (lb/gal.)	6.652
K (cSt), viscosity at 40°C	1.6
Reid Vapor pres. at 38°C (psi)	< 1
IBP	157
10% Rec	175
50% Rec	200
90% Rec	236
Flash point (°C)	45
Net Btu/lb	18,490
Net Btu/gal.	123,069

Gasoline

L ₂₅	1.2
U ₂₅	7.1
Min. Autoignition Temp. (°C)	440
Normal boiling point (°K)	306
Enthalpy of combustion(MJ/kg)	44.1
Flashpoint in air at 1 atm (°K), closed	228

Bibliography

- [1] Behke, W., **Predicting Flash Fire Protection of Clothing from Laboratory Tests Using Second-degree Burn to Rate Performance**, Fire and Materials, 8,2, p 57 – 63, 1984
- [2] Bell, K.L. and D.G. Brune, **A Revised Procedure for Evaluating Firebomb Effectiveness and Correlating Test Data** Report No. 61 JTCG/ME-72-12W
- [3] Benisek, L., Edmonson, G.K. and Phillips, W.A., **Protective Clothing – Evaluation of Wool and Other Fabrics**, pp212 –221, Textile Research Journal, April 1979
- [4] Braun, E., Cobble, V.B., Krasny, J.F., and Peacock, R., **Development of a Proposed Flammability Standard for Commercial Transport Flight Attendant Uniforms**, U.S. Department of Transportation, Federal Aviation Administration, Report No. FAA-RD-75-17b, Washington, DC, 1976
- [5] Diller, K.R. and Hayes, L.J., **A Finite Element Model of Burn Injury in Blood-perfused Skin**, ASME Journal of Biomechanical Engineering, Vol 105, pp.300-307, 1983
- [6] DiNenno, editor. **SFPE Handbook of Fire Protection Engineering**, Society of Fire Protection Engineers and National Fire Protection Association, second edition, 1995
- [7] Drysdale, D., **An Introduction to Fire Dynamics**, Wiley Interscience, First edition, 1985
- [8] Fay, J.A., Desgroseillers, G.J. and Lewis, D.H., **Radiation from Burning Hydrocarbon Clouds**, Comb. Sci. and Tech., 20, pp. 141-151, 1979
- [9] **Flame and Incendiary Materials and Devices – Foreign(U) Volume 2 (Research and Development)** NGIC-1695-146B-94, November 1994
- [10] **Flame/thermal Threat Support to Flame/thermal Protective for the Soldier** NGIC-1685-692-96, February 1996
- [11] Grummer, J., Strasser, A., Kubala, T. A. and Burgess, D.S., **Uncontrolled Diffusive Burning of Some New Liquid Propellants**, Fire Res. Abs. and Rev., 3, p.159, 1961
- [12] Hasegawa, K and Sata, K., **Experimental Investigation of the Unconfined Vapor Cloud Explosion of Hydrocarbons**, Technical memorandum of the Fire Research Institute, 12, Japan, 1978

- [13] Kalghatki, G.T., **Blowout Stability of Gaseous Diffusion Flames in Still Air**, Comb. Sci. and Tech., 26, pp.233-239, 1981
- [14] Khan, M. M. and Tewardson, A., **Characterization of Hydraulic Fluid Spray**, Fire Technology, November 1, 1991
- [15] **Land threat Environment Projectiles** Volume 5: Special Operations Forces (U) 3
- [16] **Land Warrior System Threat Assessment Report (STAR)**
- [17] LeBlanc, D., **Fire Environments Typical of Navy Ships**, MS degree thesis, Fire Protection Engineering Department, Worcester Polytechnic Institute, 1998
- [18] Mudan, K.S., **Geometric View Factors for Thermal Radiation Hazard Assessment**, F. Safety J., 12, 89-96, 1987
- [19] Mudan, K.S. and Desgroseillers, G.J., **Thermal Radiation from Hydrocarbon Fireballs**, HSE Symposium on Risk assessment, London, September 1981
- [20] Schopppee, M.M., Welsford, J.M. and Abbott, N.J., **Protection Offered by Lightweight Clothing Materials to the Heat of a Fire**, pp340-357, Performance of Protective Clothing, ASTM STP 900, American Society for Testing and Materials, 1986
- [21] Squire, J., **Assessment of alternative Materials for Combat Vehicle Crewman's Coveralls**, DCTA S&TD Technical Report No. 96/05, Defense Clothing & Textile Agency, Essex, UK, May 1996
- [22] Staples, R.A.J., Squire, J.D. and Elton, S.F., **The Threat from Flame and Intense Heat**, DCTA S&TD Technical Report No. 95/08, Defense Clothing & Textile Agency, Essex, UK, August 1998
- [23] Tribus, Myron, **Decision Analysis Approach to Satisfying the Requirements of the Flammable Fabric Act**, An address prepared by Assistant Secretary of Commerce for Science and Technology, Myron Tribus, for delivery at the Textile and Needle Trades Division, American Society of Quality Control at Greensboro, N.C., February 12, 1970
- [24] Tucker, D., **Flame/thermal Hazard Assessment**, Draft for Technical Notes, Natick Solder Center, 1998